Agricultural Water Management 216 (2019) 12–26

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Waterlogging and coastal salinity management through land shaping and cropping intensification in climatically vulnerable Indian Sundarbans

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ARTICLE INFO

Keywords:
Climate change
Water footprint
Farm pond
Water balance
Coastal saline soil

ABSTRACT

Sundarbans in West Bengal, India located in the eastern coast of the Bay of Bengal is one of the vulnerable zones subjected to abrupt climate change. The region receives 2.7 times surplus rainfall as compared to crop evapotranspiration during monsoon months causing widespread waterlogging of the low lying agricultural fields and impedes the productivity. The present study assessed the effects of different land shaping models namely, farm pond (FP), deep furrow and high ridge (RF) and paddy cum fish (PCF) systems for rainwater harvesting in restoring the productivity of degraded coastal soils in Sundarbans. A water balance was run to estimate the soil moisture, crop evapotranspiration, runoff and water depth in the reservoir during normal, excess and deficit rainfall years. The average annual harvested runoff was 2709, 1650 and 1169 m^3 per hectare in FP, RF and PCF systems, respectively. The runoff going out of the system was 19.5, 29.1 and 27.75% of the annual rainfall in FP, RF and PCF systems, respectively, whereas in monocrop rice-fallow system it was 34.6% of the annual rainfall. We estimated all the three components of water footprints (WF) i.e., blue WF (WF_{blue}), green WF (WF_{green}) and gray WF (WF_{gray}) as an aggregative indicator to evaluate environmental impact. The results indicated that total as well as the components of WF was higher in rice-fallow and rice-rice systems than in each of the land shaping system. Large scale adoption of different land shaping systems increased the cropping intensity and net farm income and there was reduction in salinity during summer and waterlogging during rainy season and overall improvement in soil quality. The dominant soluble salts identified in the study region were NaCl and $MgSO_4$.

1. Introduction

The Sundarbans is the largest contiguous mangrove ecosystem in the world located in the southern part of West Bengal, India and Bangladesh, and lies on the delta of the Ganges, Brahmaputra and Meghna rivers in the Bay of Bengal (Renaud et al., 2013; Rahman et al., 2011). Owing to its unique geographical location this world heritage site is highly vulnerable to climate change (IPCC, 2007). Principal degradation processes impacting these fragile ecosystems include coastal erosion, seawater intrusion and inundation, and salinization along with anthropogenic activities. Coastal impact in this region is more severe because of the low, flat coastal terrain, shallow coastal ocean topography in the Bay of Bengal, high density of population, low awareness of community, inadequate response and preparedness, and absence of hedging mechanism (SADR, 2007). Thus, productivity and ecosystem services, vital to functioning and sustainability of these important biomes are severely jeopardized.

The lands in these islands are highly degraded due to phenomena like saline water flooding following storm and brackish groundwater table near the soil surface due to the influence of sea or saline river water (Burman et al., 2013). In the Indian Sundarbans, around 56% of land mass lies within the coastal low-lying ecosystems with an elevation of < 5 m above mean sea level. Some parts are even below the mean sea level. The region receives high rainfall which is concentrated only over a few monsoon months (June–September). Due to this heavy concentrated rainfall in a short span, flat topography, low infiltration rate, presence of groundwater at the surface and lack of proper drainage facility, most of the cultivated fields are deeply waterlogged in *kharif* (wet) season. Farmers have no choice for alternate crops other than tall traditional landraces or old rice varieties in *kharif* (Sarangi et al., 2015). During dry winter months acute shortage of irrigation water along with increase in soil and water salinity limits the agricultural production. The coastal areas are behind many inland areas in terms of agricultural productivity and livelihood security of the farmers (Singh, 2006). Much

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https://doi.org/10.1016/j.agwat.2019.01.012
Received 16 July 2018; Received in revised form 10 January 2019; Accepted 14 January 2019
Available online 30 January 2019

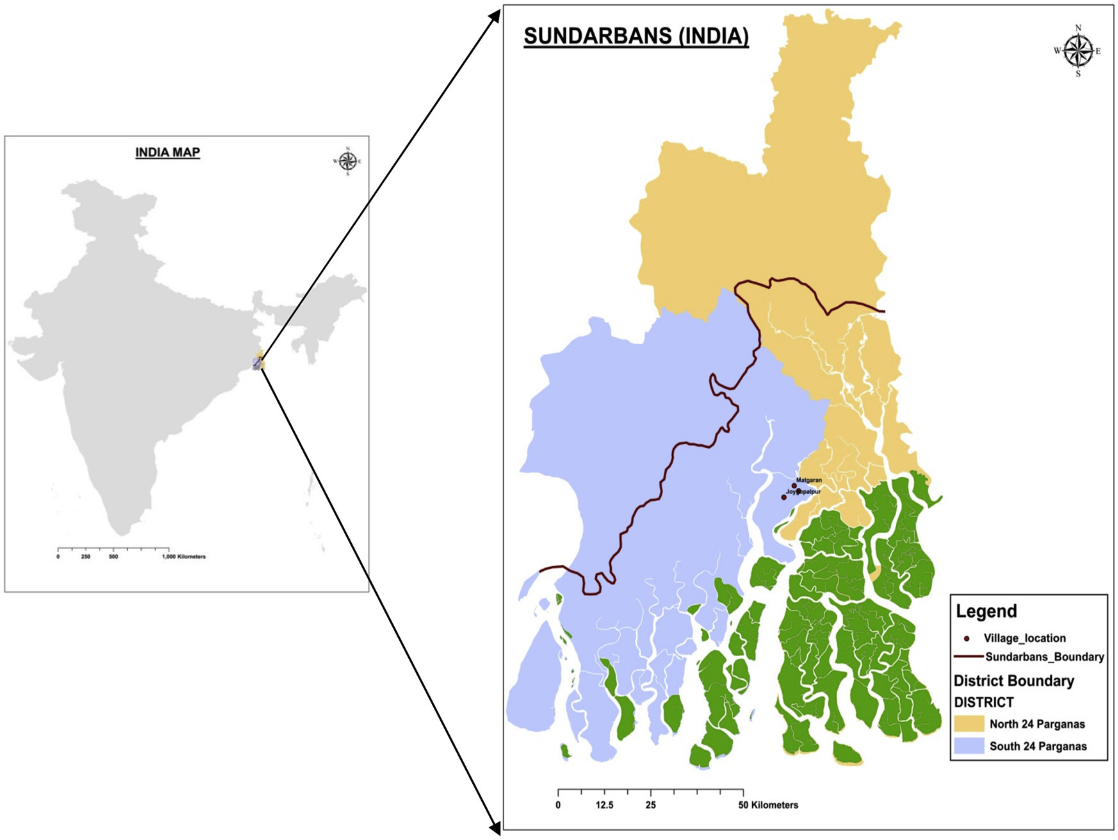

Fig. 1. Experimental site where land shaping systems were adopted.

of the coastal fringe is enclosed by bunds/ polders, some of which experience post-monsoon waterlogging that delays *rabi* (winter) season crop establishment, resulting in suboptimal crop performance (Timothy et al., 2017). The huge runoff losses of rainwater also enhance the soil erosion, and wide scale land degradation of the region.

Because of non remunerative agriculture in the region and steady growth in fishery sector, many agricultural lands are getting converted to modern commercially oriented, high output-intensive brackish water farming which poses severe environmental threats to the region.

There is a need for appropriate water and land care system for coastal area to make this fragile ecosystem into climatically more resilient. Cyclone *Alia* in 2009 further exposed the climatic vulnerability of agriculture in the Sundarbans. The area had experienced devastating floods as the ill maintained mud embankments gave way allowing the saline seawater to gush in for miles and remain stagnant for over months. The saline water also intruded the sweet water ponds killing several varieties of fish and spoilt the source of irrigation during dry season thereby, affecting the livelihood of large number of people living in the riverine area. The stagnant water increased salinity so much that even two years after *Alia*, paddy could not be established in the region (The Hindu, June 8, 2011). Therefore, demand of food security, economic development, and climate change continue to pose diverging and often conflicting challenges for water resources management in the coastal zones of the delta (Le et al., 2018).

There are opportunities for intensification of cropping through efficient use and optimal management of water, careful planning of the crop calendar, and efficient agronomic practices. Most research efforts have consequently focused on closing yield gaps under relatively favourable irrigated conditions, primarily on investigating the ways in which dry season fallowed or rainfed land-use can be intensified. Groundwater irrigation facilities are lacking, especially near the coast where shallow aquifers are mostly saline. Where environmental conditions are more permitting, the cost of deep tube well drilling and installation is still beyond the reach of most resource–poor farmers (Bernier et al., 2016). Cropping intensification of rice-fallow or rainfed systems into intensified double cropping can be achieved by increasing the availability of rainwater for irrigation use particularly during winter and summer. A comprehensive knowledge of climate fluctuations and corresponding adaptation strategies through rainwater harvesting is crucial for the progress towards sustainability. Increasing freshwater availability also pushes back oceanic saltwater intrusion during the dry season. Furthermore, local food production is vital to an island ecosystem where majority of the people still live and depend on subsistence farming (Velmurugan et al., 2015).

ICAR-Central Soil Salinity Research Institute has developed few land shaping models for water harvesting to enhance the productivity of low lying degraded land of the region and to tackle the prolonged waterlogging during monsoon season and increasing water availability during *rabi* season. Different land forming techniques such as bunding, broad bed and furrow system and rice –fish culture in Andaman and Nicobar islands improved crop diversification by enabling multiple cropping while increasing the overall farm productivity (Ravisankar et al., 2008). Srinivasarao et al. (2017) also reported that rainwater harvesting through farm pond has the potential to increase availability of water for supplemental irrigation, and offers a solution to overcome the increased frequencies of drought under climate change scenario in the semiarid tropical region. However, it was viewed by some farmers as a waste of productive land if it was not properly intensified (Kumar et al., 2016). Therefore, effectiveness of these technological interventions must be tested and fine-tuned under site-specific conditions prior to large scale adoption.

The present study was aimed to assess the effects of different land shaping models in restoring the productivity of degraded coastal soils in Sundarbans. The study was based on the hypothesis that improving soil drainage and maintaining water level within a specific depth would improve soil quality and agronomic productivity in coastal ecosystem.

We studied the hydrological impacts of rainwater harvesting in different land shaping models through water balance approach and used the water footprint as an aggregative indicator to evaluate environmental impact.

2. Materials and methods

2.1. Study area: the coastal region of West Bengal (Sundarbans)

The coastal region of West Bengal (Sundarbans), India, is situated (21°32′ & 22°40′ N latitude and 88°05′ & 89°00′ E longitude) in the district of North and South 24 Parganas (Burman et al., 2018, Fig. 1). The Sundarbans is a UNESCO World Heritage Site, two-third of which is in Bangladesh while rest one-third is in India. The region consists of 102 numbers of islands including parts of main land. Out of these, 54 islands are inhabited and the rest are under mangrove forest. The Sundarbans along the Bay of Bengal has evolved over the millennia through natural deposition of upstream sediments accompanied by intertidal segregation. The physiography is characteristically dominated by deltaic formations that include innumerable drainage lines associated with surface and subaqueous levees, splays and tidal flats. A large number of saline water rivers which criss-cross the area, influence the degree of salinity in the soil and water.

The climate of Sundarbans is moist sub-humid with hot summer and mild winter. The mean maximum air temperature during summer (March, April and May) ranges from 32.9 to 34.8 °C. The mean minimum temperature during winter (December, January and February) ranges from 13.2 to 16.6 °C. Long term climate data (1966–2015) collected at ICAR-Central Soil Salinity Research Institute, Regional Research Station, Canning Town within Indian Sundarbans indicated that Canning receives a mean annual rainfall of 1821 mm with a considerable variation [Coefficient of Variation (CV) = 18.8%, Annual Report (2015-16)]. Monsoon months (June-September) contributed 74.4% (1355 mm) to the annual rainfall, whereas pre-monsoon (March-May) and post–monsoon (October–February) months contributed 13.1% and 12.5% of the annual rainfall, respectively. Pre- and post-monsoon rainfall meets up 45 and 51% of the evapotranspiration (ET_0), whereas there was 2.7 times surplus rainfall than ET_0 during monsoon months.

2.2. Land shaping technology interventions

Different types of land shaping techniques for improving drainage facility, rainwater harvesting, salinity management and cultivation of crops and fishes for livelihood and environmental security have been developed to suit different land situations, farm size and farmers' need. The details of three land shaping techniques viz. farm pond (FP), deep furrow and high ridge (RF) and paddy cum fish (PCF) systems (Fig. 2) which were implemented in farmers' fields at Basanti block of Sundarbans are given in Table 1 (Burman et al., 2013).

2.3. Soil water balance

A water balance model consisting of four sub-model situations i.e., for non rice field, rice field, fallow land and on-farm reservoir, under each land shaping situation as well as rice monocrop and rice-rice system was used to study the hydrological impact.

2.3.1. Soil water balance for non-rice field

A simple root zone soil water balance model is used for estimating the actual evapotranspiration (AET) of crops grown without any standing water. Here the soil reservoir is divided into two layers: (i) an active layer of depth in which roots are present at any given time and from which both water extraction and drainage would occur, and (ii) a passive layer of depth [maximum root depth - root depth attained any day after sowing (DAS)] from which only drainage would occur. The two layers are distinct in the initial phase of crop growth, and their relative depths are governed by the rate of root growth. However, once the maximum root depth is attained, the entire root zone becomes only one layer. Details of the model description have been described by Mandal et al. (2002, 2007). Daily rainfall data during the growing season of the crop is used as an input. Daily runoff is estimated from the daily rainfall data using the curve number (CN) technique of the Soil Conservation Service (USDA, 1972) and combined with the soil water accounting procedure suggested by Sharpley and Williams (1990). In the model, evapotranspiration (ET) occurs at a maximum rate, called the potential evapotranspiration (PET), as long as soil water content in the root zone is more than a minimum threshold value (Dorrenbos and Kassam, 1979). When the water content falls below the threshold value, the value of ET (i.e., AET) becomes a decreasing function of the water content and PET. To obtain PET, the reference evapotranspiration (ET_0) is multiplied by the corresponding value of the crop coefficient (K_c) for the day. ET_0 (mm day^{-1}) was determined using the FAO Penman-–Monteith equation (Allen et al., 1998).

2.3.2. Soil water balance of rice field

Rice is generally grown under continuous flooded condition with about 5 cm depth of standing water during the crop growing season. For rice, the inflow components in the water balance are irrigation and rainfall, whereas evapotranspiration, percolation and surface runoff are the outflow components. The water balance equation for rice fields can be expressed as follows (Ambast et al., 1998):

$$WD = R + IR - AET - P - Q \tag{1}$$

Where, WD is water depth in the field on a given day, mm; AET = Crop evapotranspiration on that day, mm; R = Amount of rainfall, mm; IR = Amount of irrigation, mm; P = Deep percolation, mm; Q = Runoff, mm. The time period is considered as 1 day. It is assumed that there is no capillary rise from groundwater.

In the present study, rainfall in excess of bund height was considered as surface runoff. In the rice field, a bund height of 30 and 45 cm was considered under medium and low land situations, respectively under land shaping systems, whereas 55 cm bund height was considered under rice-monocrop or rice-rice system without land shaping. During *rabi* season a minimum water depth of 5 cm was maintained and irrigation with 50 mm water was applied whenever the water depth goes down to 5 cm or less. The daily percolation rate out of the root zone was computed. For rice, evapotranspiration was assumed to be equal to potential evapotranspiration as there was always standing water during the rice growing season. The K_c values for rice on weekly basis were obtained from Tyagi et al.(2000).

2.3.3. Soil water balance of fallow land

In the absence of vegetation, evaporation from fallow land occurs in two distinct stages. The first stage is termed as the energy limited or constant rate stage during which evaporation proceeds at the potential rate until the water content in the surface 10 cm of soil reaches the permanent wilting point (Campbell and Diaz, 1988). The second stage is termed as the soil limited stage or falling rate stage where hydraulic transport of subsurface water to the soil surface is unable to supply water at the potential evaporation rate. During this stage the soil appears partially dry and a portion of the evaporation occurs from below the soil surface. The evaporation rate during this stage is equal to the square of the remaining evaporable water.

2.3.4. Water balance model of the on-farm reservoir

All inflows and outflows are considered for water budgeting of on-farm reservoir (OFR) i.e., pond, ditch and furrows in FP, RF and PCF systems, respectively. The inflows are the direct rainfall in farm reservoir and surface runoff coming from the surrounding fields into it. The outflows are evaporation, seepage and percolation and irrigation

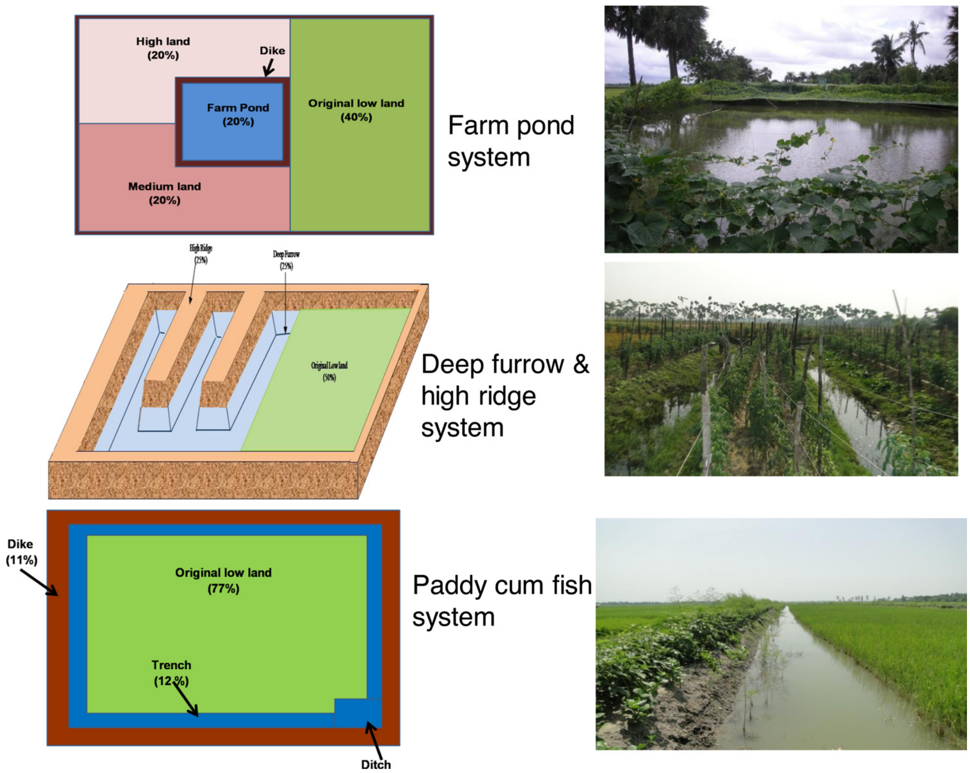

Fig. 2. Layout of different land shaping systems.

given to the crops from the reservoir (Panigrahi et al., 2005). Evaporation loss of water depends on the water spread area in the OFR at any given storage depth. The seepage and percolation loss of the OFR storage was considered at 2 mm day^{-1}.

Normally, farmers (depending on the method of irrigation) apply an irrigation depth of 20–50 mm as supplemental/ deficit irrigation in rainfed areas. The objective of supplemental irrigation is to adequately recharge the upper dry soil profile and connect it with the moist profile prevailing in the deeper soil layers, to provide continuity to the flow process (Sharma et al., 2010). We considered irrigation depth of 25 mm as supplemental irrigation and conveyance losses zero since farmers apply irrigation through plastic pipes.

Water balances for the four sub-systems i.e., in fallow, rice, non-rice and OFR were run simultaneously within each land shaping system and entire runoff was diverted towards OFR. After filling up of the OFR in each land shaping system, if there is any extra runoff it goes out of the system into natural drainage channels or estuary.

2.4. Sampling/data collection for impact assessment

Soils were collected to a depth of 0–20 cm from high, medium and low land of FP, ridge and furrow areas of RF, dike and low land of PCF systems as well as rice-rice and rice-fallow systems during December 2015 and March-April 2016. Each soil sample was a composite of three sub-samples collected from each location. Rainfall data were obtained from the automatic weather station installed in the ICAR-Central Soil Salinity Research Institute, Regional Research Station, Canning Town around 10 Km away from the study area. Observed data of soil moisture

Table 1
Description of land shaping systems.

Components	Farm pond system	Deep furrow and high ridge system	Paddy cum fish system
System description	Farm pond: 20% farm area, original low land: 40% area, Medium land (about 20 cm height from original land) 20% area and high land (about 45 cm height from original land) 20% area	Furrow: 25% farm area, ridge: 25% area and original low land 50% area.	Boundary dike 11% farm area, Trench and ditch 12% area and original low land 77 % area
Water harvesting reservoir	Farm pond	Furrow	Trench and ditch
Dimension	Average Pond dimension: Top : 30 m × 20 m Bottom : 24 m × 14 m Depth (m): 3 Side slope: 1:1	Ridge: 1.5 m × 1 m × 3 m (Top width × height × bottom width) Furrow: 3 m × 1 m × 1.5 m (Top width × depth × bottom width) Average length of ridge and furrow: 180 m Side Slope: 1: 0.75	Trench: 3 m × 1.5 m × 1.5 m (Top width × depth × bottom width) Dike: 1.5 m × 1.5 m × 3 m (Top width × height × bottom width) Average length of dike (m) : 100 Average length of Trench (m) : 78 Ditch: Top dimension (m x m) 10 × 8 Bottom dimension (m × m): 4 × 2 Depth (m): 3 Side slope of dike, trench and ditch: 1:1
Storage capacity (m^3)	Pond: 1377	Furrow: 405	Trench and ditch: 368
Farm size (m^2)	3000	2160	2670
Storage capacity per Hectare (m^3 ha^{-1})	4600	1875	1380

and water depth in the field and OFR were monitored at regular intervals during 2012 to 2014 from different land shaping systems adopted by the farmers.

2.5. Soil analysis

Around 500 g from each soil sample was separately stored in refrigerator for microbiological study. Remaining samples were dried and sieved for the physical and chemical analyses. For determining bulk density, undisturbed samples were also collected in cores along with the original samples. Samples were analyzed for basic soil properties following the standard protocols viz., pH (1:2, soil: water ratio) and organic carbon (Walkley–Black method) (Jackson, 1973). Bulk density was measured by the core method (Blake and Hartge, 1986). Soil texture was determined using the Bouyoucos hydrometer method (Gee and Bauder, 1986). Soil water retention at both field capacity and the permanent wilting point was measured using a pressure plate apparatus at 0.033 and 1.5 MPa, respectively (Cassel and Nielsen, 1986). Available water capacity was determined by subtracting the permanent wilting point value from field capacity value and multiplying it with bulk density and soil depth. Available soil N was determined by the alkaline $KMnO_4$ method (Subbaiah and Asija, 1956), which measures easily oxidizable N. Available P (Olsen P), was determined by $NaHCO_3$ extraction and subsequent colorimetric analysis (Olsen et al., 1954).

Soil salinity was determined using electrical conductivity from saturation extract of soil samples measured in the laboratory (Rhoades et al., 1999) as well as using bulk soil electrical conductivity (EC) probe (Model: C.A 6460, Eijkelkamp make) in the field at 30 cm depth interval up to the depth of 90 cm (Mandal et al., 2015). In addition to measurement of EC of saturation extract, we analyzed Na^+ and K^+ by emission spectrometry, Ca^{2+} and Mg^{2+} by ethylenediaminetetraacetic acid (EDTA) titration, Cl^- by titration with $AgNO_3$, HCO_3^- by alkalinity and SO_4^{2-} by turbidimetric procedure. Total soluble salt content was calculated by the summation of soluble Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^- and SO_4^{2-} contents.

The sodium adsorption ratio (SAR) was calculated as ratio of Na^+ concentration to square root of half of the total concentration of Ca^{2+} and Mg^{2+} expressed in me l^{-1}.,

Microbial biomass measurements were made using chloroform fumigation method (Jenkinson and Powlson, 1976; Jenkinson and Ladd, 1981).

2.6. Productivity assessment

Productivity impact of technological interventions were assessed with regard to the cropping intensity, fish productivity, net income and employment generated from representative FP, RF and PCF systems installed in waterlogged and acid/saline soils. The cropping intensity was calculated by using the following equation

$$\text{Cropping intensity} = (\text{Gross cropped area}/\text{Net sown area}) \times 100 \quad (2)$$

We collected additional data from farmers on sowing dates and the labour and monetary requirements for all major crop management operations. These included costs for land preparation, sowing, pest management, fertilizer and irrigation application, as well as harvest activities. Prices for inputs and grain and straw outputs were assigned as the average of three observations from independent dealers and buyers in local markets. These data were combined with farmers' reported local wage rates to calculate labour costs. We then conducted cost-benefit analysis for each farmer and crop observation.

2.7. Water footprints (WF)

Water footprint is expressed as the volume of water consumed or evaporated and or polluted to grow a crop per unit mass of its economic yield usually the unit is expressed as $m^3\ t^{-1}$ or $l\ kg^{-1}$ (Hoekstra and Chapagain, 2008). The WF has three components: the green water footprint WF_{green} (evaporation of profile stored soil moisture or water supplied from the rain in crop production), blue water footprint, WF_{blue} (evaporation of the irrigation water supplied from surface and renewable groundwater sources) and the gray water footprint WF_{gray} (volume of fresh water polluted in production process which represents the amount of freshwater required to mix pollutants and maintain a water quality according to agreed water quality standards). Water footprints of the crop WF_{total} ($m^3\ t^{-1}$) were thus calculated by dividing the total volume of blue, green or gray water used ($m^3\ ha^{-1}$) by the quantity of grain yield of the crop ($t\ ha^{-1}$). In this study water footprint (WF) for each crop refers to the total volume of water consumed by the crop in terms of actual evapotranspiration (AET) and the evaporation loss during land preparation for that crop. We estimated all the three components of WF i.e., WF_{blue}, WF_{green} and WF_{gray}. In the present study AET estimated through water balance for each crop and the evaporation loss during land preparation of that crop was considered as the total amount of green and blue water required for that crop. WF_{green} was calculated as (WF_{green} + WF_{blue}) - irrigation water supplied for that crop. Gray water was estimated as the amount of excess water needed to leach out the salt deposited due to capillary rise of sub surface groundwater. Singh and Kundu (2003) estimated that leaching with 1.62 cm of water removed 100% of total salt and brought down EC below 4 dS m^{-1} in 0–40 cm soil layer of coastal saline soil. We also used a leaching requirement of 1.62 cm of water met out from the early rainy season rain as grey water footprint to remove the excess salt from the field.

Water used for fish production in pond and furrows is harvested rainwater and the evaporation at potential rate from this OFR was considered as water footprint for fish and it is green water footprint as no irrigation water was used for fish production. Since the water outflows like seepage, percolation, etc. are not a loss to the catchment and again can be reused in the same area, these types of water losses were not be included for water footprint or virtual water flow accounting (Kar et al., 2016). Fishes live in water and have no need for extra water except for the limited water it absorbs and releases for its maintenance which is considered negligible.

Water footprint for each land shaping system was calculated on yearly basis based on the area weighted value of each crop ET, evaporation loss from OFR for fish water footprint, the water required leaching out the salt and the area weighted value of evaporation loss during fallow period. The constant 10 was used to convert mm into $m^3\ ha^{-1}$. For *kharif* rice crop, we considered that the entire ET was met from rainfall i.e., AET = ET_{green}. For other crops, irrigation was applied as and when required. *Rabi* (winter season) crop is an irrigated system and we allowed optimal timing of irrigation. Water productivity was expressed as physical productivity of water in kilogram of crop per m^3 of water diverted or depleted (kg m^{-3}, i.e., sum of effective rainfall and irrigation). Yields were obtained from a minimum of 10 m^2 and were moisture corrected.

2.8. Statistical analysis

One-way analysis of variance (ANOVA) was computed to compare the mean values of various parameters under different interventions. Significant difference was assessed at probability level of 5%.

3. Results and discussion

3.1. Water balance study

Comparison between the observed and simulated values of the soil water content in the active root zone under *rabi* maize and water depth under *kharif* rice crop in farm pond system during 2012 showed a close similarity (Figs. 3 and 4). The rainfall recorded annually was 1583,

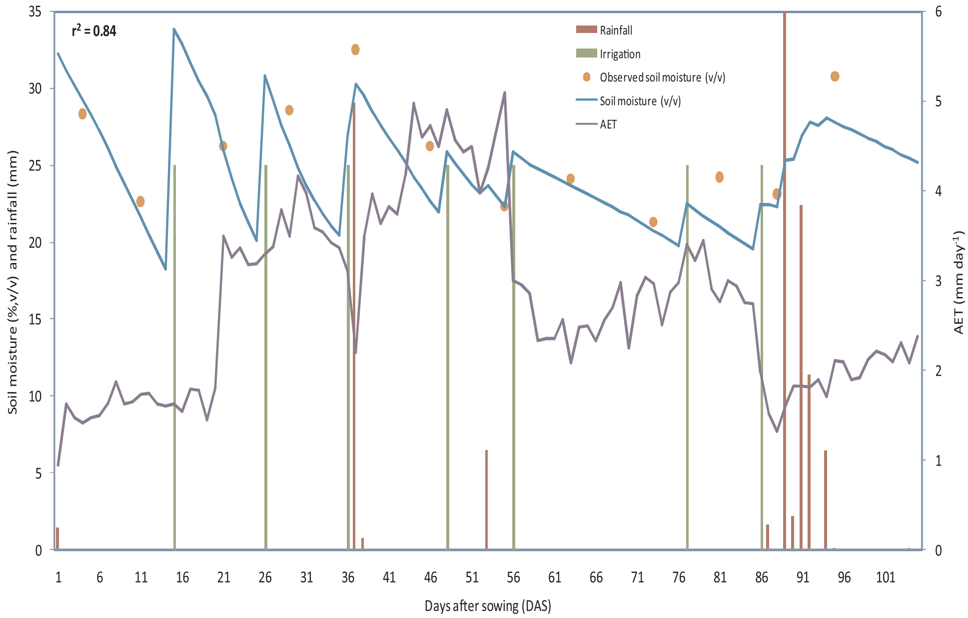

Fig. 3. Soil moisture level for maize grown in upland situation under farm pond system during *rabi* season estimated through water balance.

2164 and 1368 mm during 2012, 2013 and 2014, respectively thus showing large variation among years. The rainfall received during these three consecutive years was normal [within long period average (LPA) ± CV], excess (> LPA + CV) and deficit (< LPA-CV), respectively (Table 2). The numbers of rainy days were 72, 83 and 73 during 2012, 2013 and 2014, respectively. The pattern of fluctuation of the soil water content values throughout the growing season revealed that during the periods when there was an absence of rainfall, a gradual depletion of soil water content in the root zone was observed. Conversely, whenever there was any rainfall during the crop growing season, the soil water content in the root zone was observed to increase. Total rainfall received during maize crop was 130.9 mm and the crop was irrigated regularly with 7 irrigations, each with 25 mm and AET (289.26 mm) during entire crop growth period was almost equal to PET (289.93 mm). *Kharif* rice was grown as rainfed crop and received a rainfall of 984.8 mm, out of which 441.93 mm was lost from the field as runoff during the year 2012. The *kharif* crop didn't suffer any water stress and AET (482.98 mm) was equal to PET during entire crop growth period. The same two layer water balance model was used to estimate the root zone soil moisture level within a topo-sequence in semiarid Alfisol soils of India (Mandal et al., 2007). The model was easy to parameterize, as it only required knowledge of soil water-holding capacity, rooting depth, crop growth stages, and weather data.

3.1.1. Runoff analysis

The runoff generated was highest during 2013 among the three years studied period as rainfall and rainy days were the highest during this year (Table 2). Out of the three land shaping systems, maximum runoff harvested was under FP followed by RF and lowest under PCF system. On an average the amount of harvested runoff was 2709, 1650

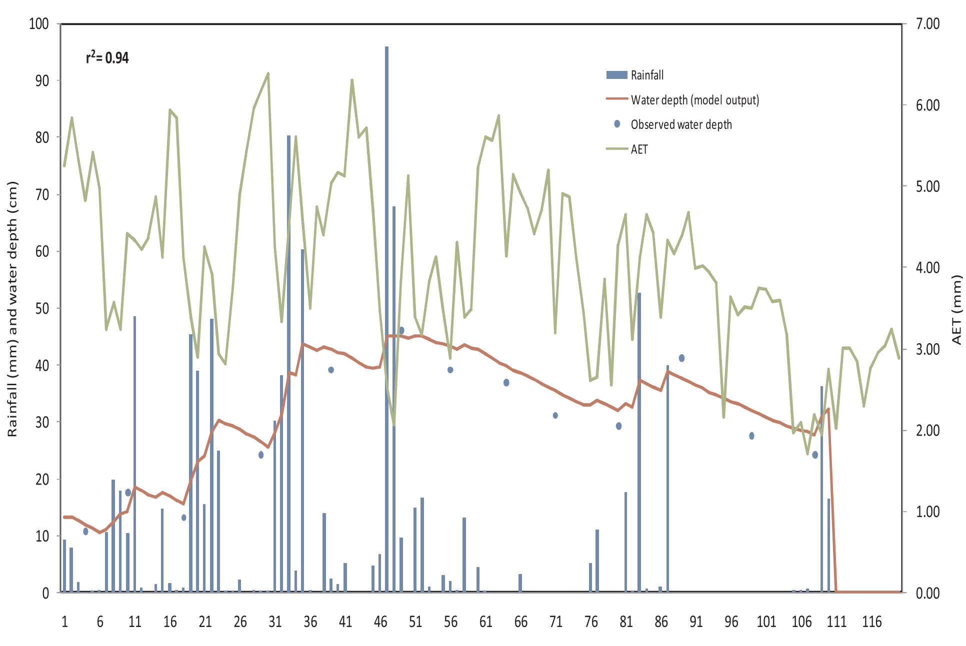

Fig. 4. Water depth for low land rice under farm pond system during *kharif* season estimated through water balance.

Table 2
Hydrologic data description under different land shaping systems during 2012, 2013 and 2014.

Description	2012	2013	2014	Average
Total rainfall (mm)	1583	2164	1368	1705
Rainy days (> 2.5 mm rain per day)	72	83	73	76
Farm Pond (FP) system				
Runoff generated (mm)	625	1028	358	670
Runoff collected (per hectare basis with 20% area under farm pond of 3 m depth) m^3	3014	2869	2243	2709
Runoff going out of the system (mm)	248	670	78	332
Net water harvested m^3 per hectare basis (harvested runoff + in-situ rainfall in farm pond)	4197	4748	3261	4069
Harvested water used for irrigation (m^3)	1700	2000	1450	1717
Deep furrow & high ridge (RF) system				
Runoff generated (mm)	670	1078	401	716
Runoff collected (per hectare basis with 25% area under furrow and 25% area under ridge with a depth of 1 m) m^3	1804	1335	1812	1650
Runoff going out of the system (mm)	430	899	160	496
Net water harvested m^3 per hectare basis (harvested runoff + in-situ rainfall in furrow)	3453	4859	3599	3970
Harvested water used for irrigation (m^3)	1062	938	1125	1042
Paddy-cum-fish (PCF) system				
Runoff generated (mm)	558	977	295	610
Runoff collected (per hectare basis with 12% area under trench of 1.5 m depth) m^3	1001	938	1567	1169
Runoff going out of the system (mm)	428	877	117	472
Net water harvested m^3 per hectare basis (harvested runoff + in-situ rainfall in trench and ditch)	1001	3017	2001	2006
Harvested water used for irrigation (m^3)	798	750	825	791
Rice-fallow system runoff generated (mm)	539	949	281	589
Rice-rice system runoff generated (mm)	442	881	180	510

and 1169 m^3 of water in FP, RF and PCF systems, respectively. As the region received a good amount of rainfall, the harvested total rainwater (harvested runoff + rainfall at OFR) per year was calculated as 4069, 3970 and 2006 m^3 in FP, RF and PCF land shaping systems, respectively. Though the year 2013 received excess annual rainfall, maximum runoff was harvested during 2012 in case of FP system, whereas it was during 2014 in case of RF and PCF when the year 2014 was a deficit rainfall year. The amount of collected runoff in each land shaping system depend on the intra seasonal rainfall distribution rather than the total amount of annual rainfall.

Around 42%, 26% and 39% of harvested rainwater in case of FP, RF and PCF systems were used for irrigation. Under different land shaping systems, 332 mm–496 mm of rainwater which accounts 19–29% of average annual rainfall goes out as runoff, whereas under rice-rice and rice-fallow system around 29–35% of rainfall goes out as runoff and the field remain waterlogged for a long time even after harvest of *kharif* rice crop.

3.1.2. Water depth and soil moisture contents

The depth of submergence recorded for both coastal low land as well as land under land shaping closely followed the rainfall pattern of the region (Fig. 5). During the rainy season (24–39 SMW) (SMW: standard meteorological week) the depth of submergence ranged from 8 to 49 cm in coastal low land under rice-monocrop system compared with 4–38 cm and 3–27 cm in low and medium land conditions under land shaping systems. Besides that, the low land without land shaping remained inundated up to 19 cm till 48 SMW whereas, most of the water drained out after 45 SMW under land shaping situation. Due to poor or non-existence of drainage facilities, flat topography, low-lying lands and heavy rainfall, the fields under rice-monocrop system remained waterlogged with a depth of more than 30 cm from July to October. Much of the coastal fringe is enclosed by embankments and experience post-monsoon waterlogging that delays *rabi* season crop establishment, resulting in suboptimal crop performance.

Out of three land shaping systems under study the FP is perennial and holds water throughout the year for fish farming, whereas the furrow and ditch of other two systems i.e., RF and PCF almost dry out as the water depth going down below 10 cm during the month of March after 12 SMW (Fig. 5). As soon as the monsoon breaks rainwater start accumulating from 24th SMW in the on-farm reservoir. From September 2nd week to November 2nd week most of the OFRs remain full.

Temporal variation in soil moisture content in the root zone layer was estimated for 52 SMW in uplands of FP and ridge in RF and dike in PCF systems (Fig. 6). On an average the upland soils under FP, soils in ridge under RF and soils in dike under PCF system hold 26.6, 24.6 and 23.6% soil moisture (v/v), respectively throughout the year whereas, dominant rice mono-crop systems had only 14.2% soil moisture in the root zone during dry period of 1–27 SMW. High land under FP system had slightly (1–2%) higher moisture than RF and PCF system up to February when water was available for irrigation in all the land shaping systems. After February hardly any water was available for irrigation under RF and PCF systems. During 9–15 SMW, in high land condition of the FP system the soil moisture was 6–15% higher than in other land shaping systems because of irrigation opportunity under the FP system. In rice-monocrop system there was 9–17% less soil moisture than in raised land of the other land shaping systems during dry period up to June. After that, as the monsoon breaks, rice-monocrop system had higher moisture and submergence took place from July onwards. During rainy season from 28 to 49 SMW, the flat low land under rice-monocrop system remained under saturation/submergence. In contrast, during heavy rainfall raised beds remained above the saturation point only for few hours/ days before attaining the field moisture capacity. In case of upland situation under vegetable cultivation though the monsoon rain was 2–3 times the PET requirement, the crop sometimes suffered intermittent dry spells and one or two irrigation was applied to meet its ET demand.

In coastal areas one of the primary concerns is the tackling of surface water congestion during the monsoon period as a major portion of the land becomes heavily waterlogged. The main factors that contribute to waterlogging in these regions are heavy and intensive rainfall and impeded natural drainage because of their distinct physiography and relief (Rao and Ambast, 1996). The technology for the improvement of agricultural productivity in these areas primarily concerns with the tackling of surface water congestion in the monsoon season. Outlet availability for gravity drainage is limited due to flat and low-lying topography. Field drainage systems are practically non-existent, which is partly due to low density of the main drainage network and partly to the small size of the holding (about 0.3 ha or less). Land owners or share croppers are therefore, not inclined to sacrifice land for a more intensive network of drainage canals. The rice fields in the higher parts of

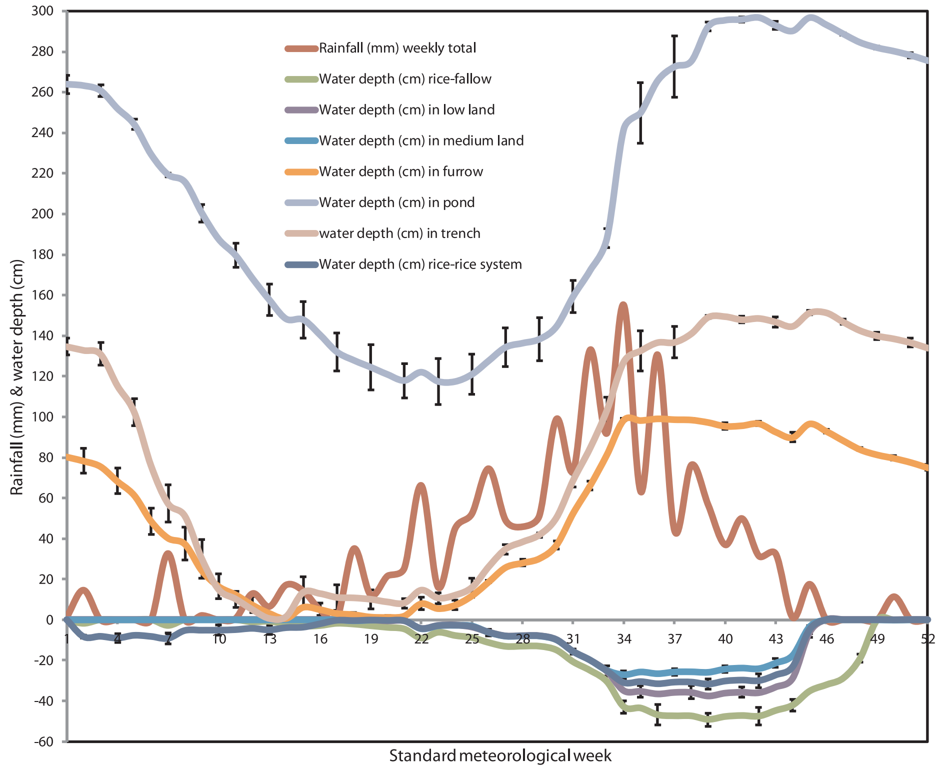

Fig. 5. Water depth under different land shaping systems estimated using water balance during 2012–2014; error bars are ± SE within years.

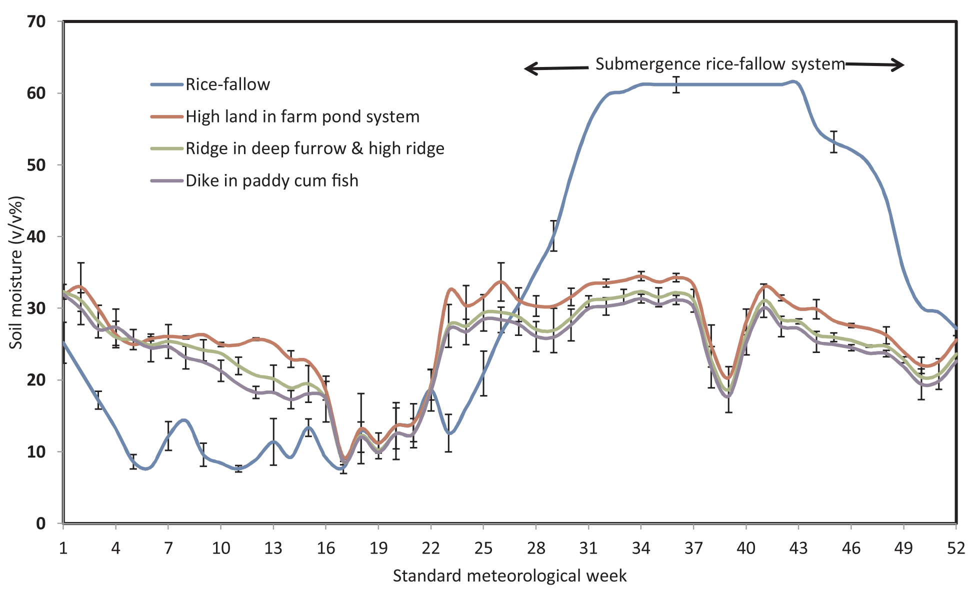

Fig. 6. Soil moisture level (v/v%) under high land situation under different land shaping systems estimated using water balance during 2012–2014; error bars are ± SE within years.

the land are usually not bunded and runoff from these parts also contributes to the waterlogging problems in the lower reaches which along with in-situ intense rain further aggravate the problem. The drainage development is still at the stage of flood control rather than to meet agricultural requirements. Some improvement in crop production under land shaping systems was achieved by introducing improved crop planning based on rainfall patterns for different land situations and adapting relatively high yielding varieties. Our results confirmed that construction of OFR in farm area through land shaping reduced the water depth in rice field than the farmers' practice and ultimately reduced drainage congestion in the surrounding areas (Fig. 5). As farmers were getting excess rainwater as irrigation in the field to overcome intermittent drought, assured availability of water in OFR encouraged farmers to maintain desirable water regime for high yielding crops and adopt modern agricultural practices. The soil moisture regime in the raised bed under land shaping systems during 22 to 52 SMW was within the available range of 18–32% which created great opportunity to raise vegetables and other arable crops even during the intense rainy season. During the pre-monsoon rains, the *rabi* crops were less affected by excess moisture under land shaping systems than in level fields.

The salinity of the harvested rainwater in the different land shaping systems was monitored periodically (Fig. 7). The highest salinity was

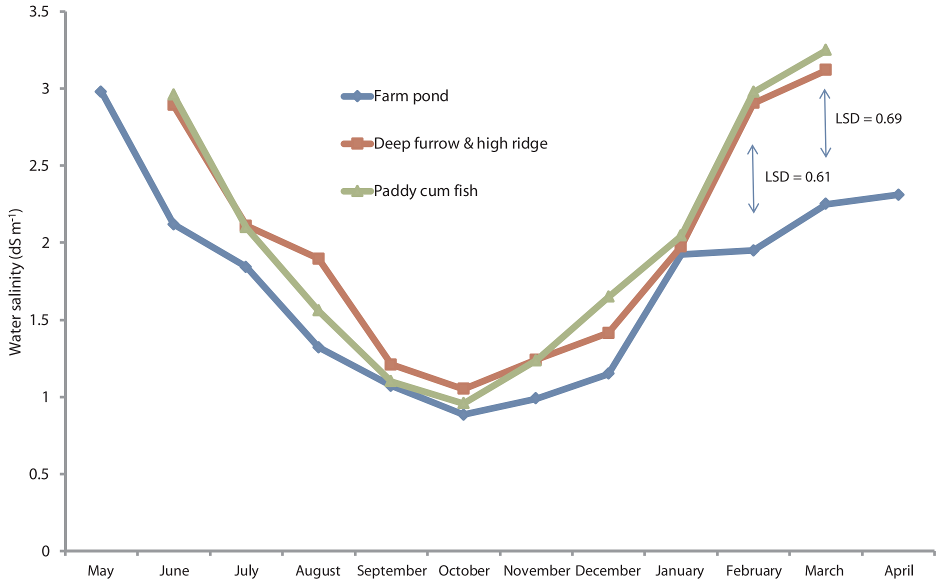

Fig. 7. Salinity level in harvested water under different land shaping systems.

observed during dry months and it decreased to lowest value during the monsoon months. Salinity of water indicated that it was suitable for irrigation as well as for the fish cultivation.

3.2. Assessing soil properties

There was no statistically significant ($p \le 0.05$) variation in soil pH between the seasons. Soils collected from different sites under different land configuration exhibited variation of pH between neutral to acidic range. The pH during winter ranged between 5.23 and 6.33 with a mean value of 5.75 (Table 3). The pH was slightly higher during summer than in winter and it varied between 5.54 and 6.72 with a mean value of 6.18 in all the systems. The salinity build up in soil under different land situations showed seasonal variability. Soil salinity of the saturation paste extract (EC_e) was $< 4\,dS\,m^{-1}$ in all the systems just after *kharif* season during winter. EC_e ranged from $2.1\,dS\,m^{-1}$ under low land situation in FP system to $3.82\,dS\,m^{-1}$ in rice fallow system. Salinity increased in all the land use systems as the summer progressed and it ranged between 2.62 and $9.77\,dS\,m^{-1}$ with a mean value of 4.18. This was mainly due to upward capillary rise of saline groundwater present at shallow depth ($< 2\,m$ during dry season) following evaporation from the soil surface which resulted in gradual accumulation of salts in the surface depth. It was observed that the salinity build up in the soil of different land shaping area was relatively less compared to original salt affected coastal low land under monocrop rice system. Less soil salinity in the land shaping systems might be due to increased distance between the saline groundwater table and the surface soil resulting in decreased accumulation of salt through upward capillary flow and or due to the presence of harvested rainwater in OFR. The soil at the base of ridges/ dikes/ raised beds remained almost saturated with fresh water as long as there was harvested water available in the OFR thereby, lowering the soil water potential and less upward capillary

Table 3
Effect of land shaping systems on seasonal variation of soil salinity and dissolved ions.

Parameters	Units	Rice monocrop	Rice-rice	FP low land	FP medium land	FP high land	RF low land	RF ridge	PCF low land	PCF dike
Winter										
pH		5.51 aA	5.91 aA	6.33bA	6.31bA	5.96abA	5.48 aA	5.56 aA	5.23 aA	5.44 aA
EC_e	$dS\ m^{-1}$	3.82 aA	3.28bA	2.1 cA	2.47cA	2.57 cA	2.89cbA	3.12bA	2.46 cA	2.88cbA
Ca^{2+}	$me\ l^{-1}$	6.45 aA	5.32 aA	7.76bA	8.06bA	5.88 aA	6.72 aA	7.06abA	6.91 aA	6.53 aA
Mg^{2+}	$me\ l^{-1}$	11.04 aA	9.63bA	7.85 cA	7.22 cA	8.83bcA	7.68 cA	9.60bA	5.57 dA	6.61 dA
K^{+}	$me\ l^{-1}$	0.68 aA	0.60 aA	0.58 aA	0.46 aA	0.27bA	0.51 aA	1.26 cA	0.53 aA	0.65 aA
Na^{+}	$me\ l^{-1}$	30.39 aA	23.12bA	11.23 cA	22.88bA	14.58 cA	13.22 cA	18.28 dA	14.26 cA	13.22 cA
Cl^{-}	$me\ l^{-1}$	24.54 aA	21.01 aA	9.39bA	14.04 cA	18.21acA	13.22 cA	16.28 cA	6.3bA	11.7bcA
HCO_3^{-}	$me\ l^{-1}$	2.26 aA	1.28abA	1.66 aA	1.45abA	1.75 aA	1.75 aA	2.05 aA	1.04bA	2.02 aA
SO_4^{2-}	$me\ l^{-1}$	14.76 aA	9.76bA	12.5abA	14.2 aA	13.9 aA	8.88bA	12.11abA	9.12bA	13.45 aA
SAR		10.28 aA	8.46 aA	4.02bA	8.28 aA	5.38bA	4.93bA	6.33bA	5.71bA	5.16bA
Summer										
pH		5.54 aA	6.30bA	6.65bA	6.72bB	5.85 aA	6.37bB	6.65bB	6.00abB	5.54 aA
ECe	$dS\ m^{-1}$	9.77aB	5.33bB	2.64cB	2.62 cA	2.82 cA	3.59cB	3.55cB	2.74 cA	3.92cB
Ca^{2+}	$me\ l^{-1}$	14.03aB	9.96bB	9.98bB	8.72bB	8.06bB	9.22bB	11.59cB	6.03 dA	9.41bB
Mg^{2+}	$me\ l^{-1}$	26.5aB	15.44bB	9.22 cA	10.38cB	13.82bB	12.86bB	10.94 cA	10.18cB	5.38 dA
K^{+}	$me\ l^{-1}$	5.19aB	3.80bB	2.72cB	2.73cB	2.24cB	2.82cB	4.62abB	2.24cB	2.16cB
Na^{+}	$me\ l^{-1}$	61.04aB	35.35bB	30.97bB	23.03 cA	15.52deA	17.65 dB	18.73 dA	15.38deA	12.49eA
Cl^{-}	$me\ l^{-1}$	77.74aB	38.3bB	26.44cB	30.88cB	31.95cB	25.16cB	17.63 dA	16.20 dB	18.91 dB
HCO_3^{-}	$me\ l^{-1}$	7.34aB	3.65bB	4.64bB	3.82bB	2.98bA	3.32bB	3.61bB	3.32bB	3.85bA
SO_4^{2-}	$me\ l^{-1}$	41.28aB	19.76bB	31.71cB	19.7bA	25.2bcB	20.31bB	21.4bB	14.9cB	21.4bB
SAR		13.56aB	9.92bA	10.00bB	7.45cB	4.69 dA	5.31 dA	5.58 dA	5.40 dA	4.59 dA

Values with the same lowercase letters within land uses in a season are not significantly different at $P < 0.05$; values with the same uppercase letters within summer and winter seasons are not significantly different at $P < 0.05$. FP, farm pond system; RF, deep furrow and high ridge system; PCF, paddy cum fish system.

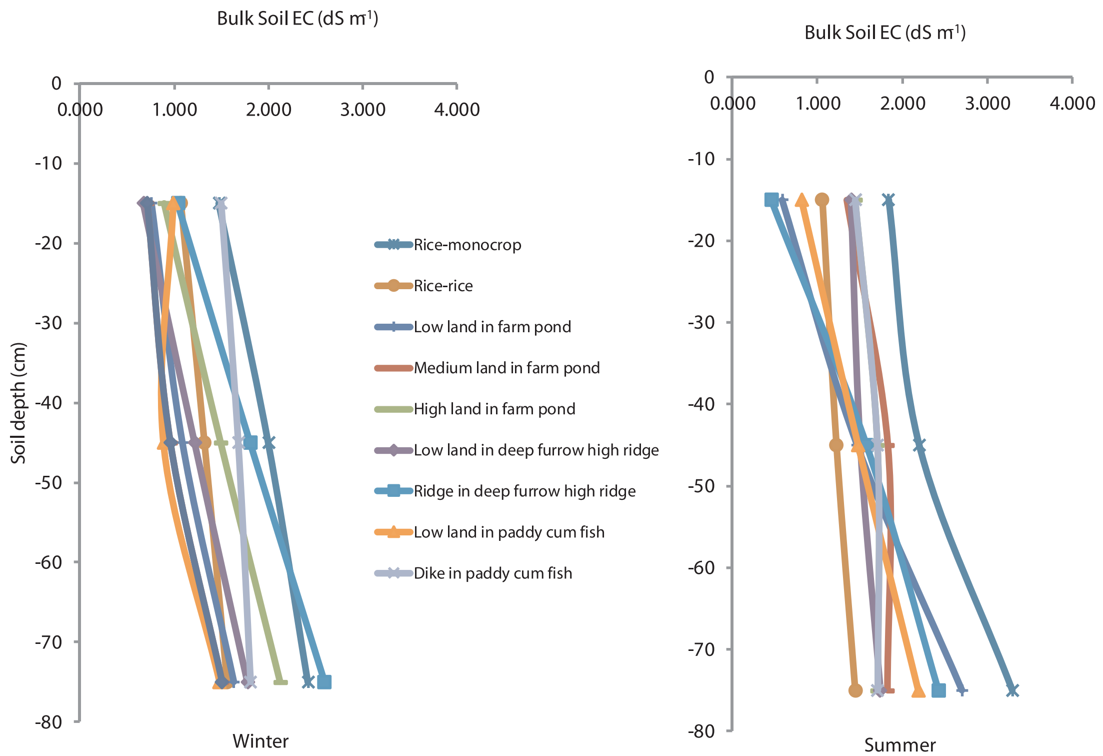

Fig. 8. Bulk soil salinity at 0–30, 30–60 and 60–90 cm depth under different land shaping systems.

movement of saline groundwater. The irrigation during *rabi* season also kept the soil wet and not allowing it to dry immediately after *kharif* thereby, preventing salinity build up under different land shaping models as well as rice-rice system.

Bulk soil salinity (EC_a) measured up to 90 cm depth varied between 1.06–1.96 dS m^{-1} during winter to 1.24–2.45 dS m^{-1} during summer. Bulk soil salinity increased with the increase in the depth during both the season (Fig. 8). The results indicated that in land shaping systems not only the surface soils but also the soils at higher depth (around 90 cm) was less saline than rice monocrop system. A calibration curve was developed between EC_a and EC_e for the studied soils. The data showed a high degree of correlation (r^2 = 0.782; $EC_e = 2.659xEC_a - 0.167$). Assessing in-situ soil salinity in root depth using bulk soil EC probe is quick, reliable and easy to take measurement to understand the spatio-temporal variability of soil salinity for management decisions.

There was a seasonal effect on soluble ionic composition of soils. The concentration of all cations and anions studied were comparatively more during the summer season than in winter season. Na^+ accounted for the highest percentages of total soluble cations content, ranging from 48.5 to 70.7% during winter and 46.1 to 63.5% during summer and it was highest in rice monocrop system. After Na^+, Mg^{2+} was the dominant cation followed by Ca^{2+} and K^+.

Among the anions, Cl^- was the dominant anion, followed by SO_4^{2-} and HCO_3^-. The carbonate (CO_3^{2-}) content was negligible in most of the soil samples and data has not been presented. The percentage of Cl^-, SO_4^{2-} and HCO_3^- content to total soluble anions ranged from 32.3 to 57.7, 36.2 to 58.0 and 6 to 10.4, respectively during winter and 34.2 to 53.7, 38.2 to 55.5 and 7.2 to 13.6, respectively during summer.

Soil total soluble salt content varied from 1.003 to 1.7 g l^{-1} during winter and increased to 1.49 to 5.19 g l^{-1} during summer (Fig. 9). SAR greatly differed under different land shaping systems which ranged from 4.02 to 10.28 during winter and increased to 4.59 to 13.56 during summer. SAR was significantly higher in rice monocrop system than in other land shaping systems. These findings agree with previous reports on the soils of the studied region (Bandyopadhyay et al., 2003; Tripathi et al., 2007).

Under land shaping systems, increased cropping intensity reduced the EC indicating that it promoted the downward movement of salts and reduced the soil salinity in surface soil. Compared with rice monocrop system the SAR in different land shaping situations reduced by 39% during winter and 54.3% during summer whereas in rice-rice system the reduction was 13.6% during winter and 26.8% during summer. Salt affected soils can be influenced easily by land management practices than other soil types and selecting suitable land use to restore the degraded soils caused by soil salinization is the essential prerequisite of sustainable agriculture in a specific region (Yu et al., 2018).

The ratios of $Na^+/(Cl^- + SO_4^{2-})$ and $HCO_3^-/(Cl^- + SO_4^{2-})$ for the entire study area were < 1. Thus application of amendments (e.g. gypsum) was not required. Instead, continuous natural leaching through rainwater impounding reclaimed the *Aila* affected agricultural lands. Under land shaping situation, improved drainage of the raised beds removed salts and toxic substances from the raised beds over time because raised beds provide better opportunities to leach salts from the soil (Bakker et al., 2010).

The regression analysis between EC_e with different soluble ions and SAR showed highly significant linear regression relationships (Fig. 10). The slope values of regression relationship indicated that Cl^-, SO_4^{2-} as anion and Na^+ followed by Mg^{2+} and Ca^{2+} as cation in soil solution are responsible for salinity. The results indicated that NaCl followed by $MgSO_4$ are the dominant soluble salts in studied regions. Subba Rao et al. (2011) mentioned that NaCl and Na_2SO_4 are important soluble salts with abundance of soluble cations, free from sodicity problems are in general characteristics in most of the coastal soils of India. The ionic radius as well as charge density of Na^+ and Cl^- are similar and same is the case for Mg^{2+} and SO_4^{2-} which leads to formation of salts like NaCl and $MgSO_4$ in soil solution (Zhang and Norton, 2002). Soil EC is highly correlated to different soluble salt content, and thus was broadly used as the reliable and easily measured indicator of soil salinity (Herrero and Castaneda, 2013).

The problems of soil salinity in raised land may be cured by surface drainage and disposal of water with dissolved salts via the basins. Such

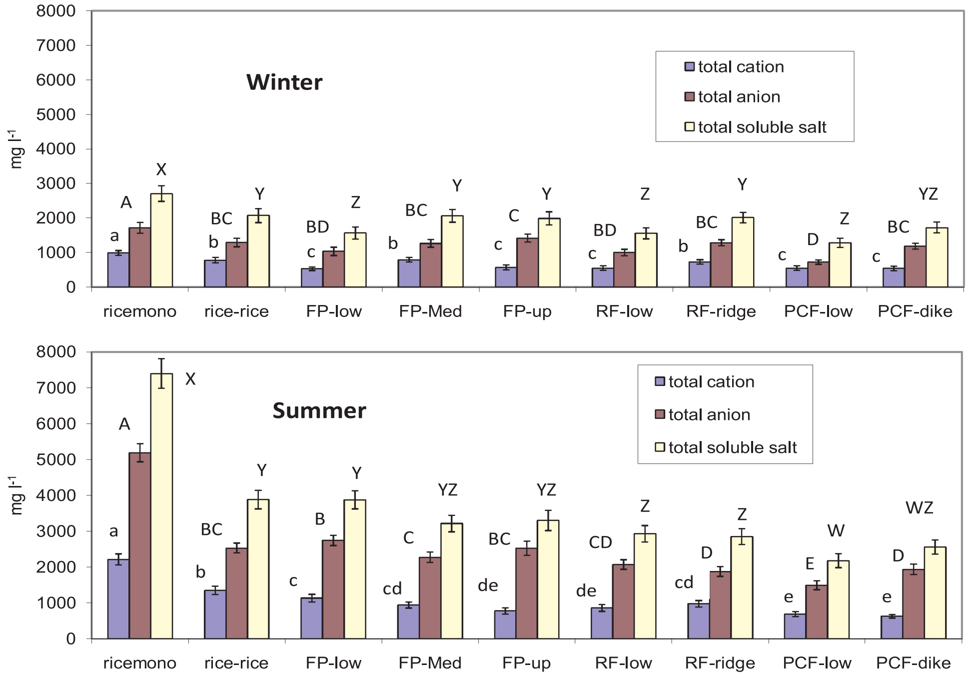

Fig. 9. Changes in total soluble cations, anions and salt content under different land shaping systems. Ricemono, monocrop rice system; FP-low, FP-Med and FP-up are low land, medium land and high land conditions in farm pond system; RF-low and RF-ridge are low land condition and ridge in deep furrow and high ridge systems; PCF-low and PCF-dike are low land condition and dike in paddy cum fish system. Values with the same uppercase letters between W, X, Y, Z within land uses are not significantly different at P < 0.05 for total soluble salts; values with the same uppercase letters between A, B, C, D, E within land uses are not significantly different at P < 0.05 for soluble anions; values with the same lowercase letters between a, b, c, d, e within land uses are not significantly different at P < 0.05 for soluble cations.

lands are less susceptible to resalinization during the dry season as evident from lower soluble salts in high land situation of different land shaping systems (Fig. 9). During *kharif* season, the raised beds under different land shaping situations remained below the saturation level while the surrounding areas were under varying levels of submergence because of low flat topography. The bunds also prevented intrusion of seawater directly into the fresh water (rainwater) harvested in the furrows as was evidenced from relatively lower chloride and sulphate concentrations.

We also studied the soil fertility level and all land use systems had high (> 0.75%) organic C contents (Table 4). The organic C levels in coastal soils were higher compared to other tropical Indian soils. Rice is the dominant cropping system in coastal region during *kharif* season. Except in high land situation where farmers grow vegetables round the year, in all other situations, farmers were growing paddy during *kharif*. The fields remain submerged for more than 6 months in the region that reduce the rate of organic matter decomposition and thus maintain high level of soil organic C. Available soil N was low (< 280 kg ha^{-1}) across the land use systems. Farmers in the coastal region hardly apply any fertilizer or very low doses (< 100 kg ha^{-1} of urea) of nitrogenous

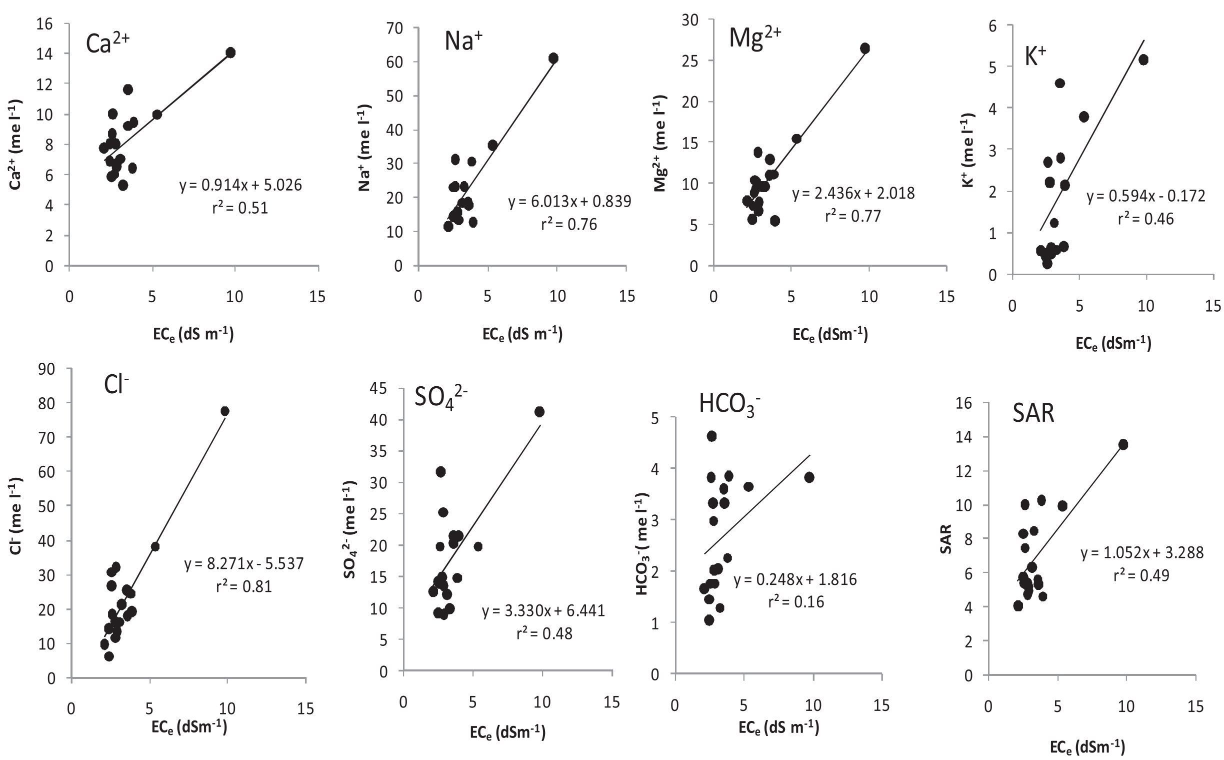

Fig. 10. Regression relationship between EC_e and soluble ions and SAR (sodium adsorption ratio).

Table 4
Effect of land shaping systems on soil properties.

Parameters	OC %	Av N Kg ha^{-1}	Av P	Av K	Bulk Density Mg m^{-3}	MBC μg g^{-1}
Rice-monocrop	0.76a	122.8a	9.3a	514.6ac	1.50ab	187.6a
Rice-rice	0.91b	124.1a	18.1b	474.5a	1.47a	288.2bc
Farm pond system- low land	0.86b	114.3a	27.5c	394.5b	1.59b	243.8b
Farm pond system- medium land	0.87b	129.5a	36.9d	479.2a	1.54b	279.1b
Farm pond system- high land	0.93b	194.2b	49.8e	519.3ac	1.56b	342.2 cd
Deep furrow and high ridge system-low land	0.79ac	169.3b	24.7c	642.2d	1.58b	291.1bc
Deep furrow and high ridge system- ridge	0.82c	234.8c	46.6e	499.8ac	1.51ab	376.3d
Paddy cum fish system-low land	0.81c	178.3b	39.2de	442.0ab	1.60b	225.6ab
Paddy cum fish system-dike	0.85bc	198.2b	46.1e	549.1c	1.54b	325.9c

OC, Organic C; Av N, Available N; Av P, Available P; Av K, Available K; MBC, Microbial biomass carbon. Values with the same lowercase letters within land uses are not significantly different at $P < 0.05$.

fertilizer during *kharif* season not only for rice but even for vegetables because of high risk of crop failure and poor economic condition. Obviously soil N level was low in all the land use systems (Table 4). Available P was medium to high in all the land use systems and maybe because of continuous application of diammonium phosphate fertilizer (DAP) which might have contributed to the build up of high level of available P in these soils. All the soils were rich in available K.

The bulk density (BD) of the soil varied from 1.47 to 1.60 Mg m^{-3} and it was lowest in rice-rice system whereas highest BD was recorded under low land situation in PCF system. Bulk density of the soils was relatively high, though the soils have higher organic matter as the regions have Inceptisols with heavy textured soils. The saline coastal soils are dominated by sodium salts and the exchange phase is dominated by Na^+ (Rengasamy, 2016). The adsorption of Na^+ in the exchange phase from soil water depends on the proportion of divalent cations in soil solution, usually indicated by SAR. Water molecules react with the adsorbed cations on soil particles inducing a weakening of soil aggregates, and as a consequence aggregates slake and clay particles disperse. In addition to sodium, the soils have high K^+ and Mg^{2+} which can also increase soil swelling and dispersion of soil clays resulting in reduced water and air flow, high soil strength and soil crusting.

The highest levels of microbial biomass carbon (MBC) were detected in soils of ridges in RF system. The MBC of soils collected from different land use systems varied from 188 to 376 μg g^{-1}. The leftover stubble and root masses of the crops under different land shaping models with higher cropping intensity increased the organic C status of the soil. Higher level of organic C dictated the trend of soil MBC due to higher substrate availability to microorganisms (Tripathi et al., 2007) in soils under land shaping situations. In addition, the lowest MBC in rice monocrop system could be attributed to soil desiccation during summer under fallow (Van Gestel et al., 1992) as well as increase in salinity (Batra and Manna, 1997; Rietz and Haynes, 2003).

3.3. Economics

Agronomic productivity of land shaping system installed in coastal waterlogged soils was significantly more than that of land without land modification (Table 5). The land shaping systems constructed from excavated soil facilitated the drainage of excess water and created better soil physical conditions for improved crop growth. This was evidenced from the successful cultivation of different vegetables even during the rainy season and integration of fish culture in the production system. Vegetable grown in the raised bed accounted for 43, 54 and 27%, and fish contributed 24, 22 and 14% of the total farm income under FP, RF and PCF systems, respectively. The harvested rainwater in furrows, trenches and ponds was used for providing 6–7 irrigations each of 25 mm depth for crops grown during the dry season. The system also provided ample scope for crop diversification, thereby increasing the cropping intensity up to 178–205% compared with that of only 100% cropping intensity under farmers' practice without any interventions. Year round crop cultivation and fish culture enhanced employment generation of 218–227 man-days under land shaping systems than control, rice monocrop with 87 man-days and rice-rice with 162 man-days. Thus integrated system had higher B: C ratio and net farm income increased from INR (Indian rupee, one US dollar ≈ 69 rupees) 19,168 ha^{-1} in rice monocrop system to INR 0.87–1.43 lakhs ha^{-1} under land shaping systems. Therefore, improvement in degraded land and diversification of agricultural systems because of different interventions increased productivity and livelihood security of population in coastal degraded lands of Sundarbans.

3.4. Water footprint/productivity

Water productivity based on grain yields were highest in RF followed by FP, PCF and rice-rice system and lowest in control under rice-monocrop. The lowest WF was recorded under FP system (Table 6) on the other hand, the WF was higher under rice-monocrop system without any intervention of land shaping techniques. Rice was grown during *kharif* as rainfed crop, no blue water was used for its growth and the grey water was used to leach out excess salt that had accumulated during summer.

The computation of water productivity and WF was introduced in the present study as a metric to assess water use in the production of important commodities in a system perspective and was considered to be a comprehensive indicator from the standpoint of better water management. Green water is the infiltrated rainfall held in the root zone soil. It rarely has competitive users, whereas blue water has several, e.g., industry and households. The opportunity cost of green water is low, compared with that of blue water (Liu et al., 2009), thus sustainable water usage encourages the use of green water instead of blue water. In land shaping system the entire blue water used is harvested rainwater accumulated in OFR whereas, under rice-rice irrigated system groundwater plays the central role in water supply. There is necessary to distinguish groundwater in blue water component for better water use study (Wang et al., 2015). This study established a relationship between crop WF and agricultural land use in a system perspective to give support to the development and implementation of policies on agricultural land use and water management. The overall aim was to alleviate water stress and to ensure sustainable cropping system intensification in the vulnerable coastal regions of India. In most cases water policies focused mainly on the management of blue water whereas, green water management was often marginalized by water resource planners. Measures for green water utilization through rainwater harvesting should be emphasized for sustainable water management policies in Sundarbans region.

In rainfed agriculture, drought is a common phenomenon due to either a late onset or early withdrawal of monsoon or dry spells within the cropping season. Not only in semi-arid and sub-humid agroecosystems, dry spells (short periods of drought during critical growth stages) occur in almost every rainy season even in the moist sub-humid

Table 5
Impact of different land shaping systems in Sundarbans region.

Land shaping models	Land situation created	Crops: *Kharif* season	Crops: *Rabi*/summer season	Cropping intensity	Total Rice Equivalent Yield (REY) (Kg ha^{-1})	Total Net Return (Rupees kg^{-1})	Benefit-cost ratio	Employment generation (man days hh^{-1} yr^{-1})
Farm Pond system (FP)	(a) Pond (20%)	Fish	Fish	205%	16652a (164)	143740a (8680)	2.98	227a (8)
	(b) High land and dikes (20%)	Vegetables, fruit crops	Vegetables, fruit crops					
	(c) Medium land (20%)	High yield variety (HYV) Rice	Vegetables, low water requiring field crops					
	(d) Original low land (40%)	Paddy + fish	Low water requiring field crops/ vegetables, short duration rice					
Deep furrow & high ridge system (RF)	(a) Furrows (25%)	Paddy + fish	Fish	189%	13828b (148)	100091b (7280)	2.26	218a (7.5)
	(b) Ridges (25%)	Vegetables & fruit crops/ multi-purpose tree species	Vegetables & fruit crops/ multi-purpose tree species (MPTs)					
	(c) Original low land (50%)	Rice under paddy + fish	Low water requiring field crops/ vegetables					
Paddy-cum-fish system (PCF)	(a) Trenches (11%)	Fish under paddy + fish	Fallow	178%	12493b (153)	87502b (6870)	2.17	223a (8.2)
	(b) Dikes (12%)	Vegetables & fruit crops/MPTs	Vegetables & fruit crops/MPTs					
	(c) Original low land (77%)	Paddy + fish	Low water requiring field crops/ vegetables					
Control (farmers' practice)	Low land	Paddy	Fallow	100%	3050c (110)	19168c (2510)		87b (3.5)
Rice-rice	Low land	Paddy	Paddy	200%	7830d (125)	50912d (3800)	1.89	162c (5.6)

Results are shown as mean and SE in parentheses. Values with the same lowercase letter within land uses are not significantly different at $P < 0.05$.

Table 6
Water footprint and water productivity under different land shaping systems.

Land modification system	Water productivity (kg m^{-3})	Green water footprint ($m^3 t^{-1}$)	Blue water footprint ($m^3 t^{-1}$)	Gray water footprint ($m^3 t^{-1}$)	Total water footprint (($m^3 t^{-1}$)
Rice-monocrop	0.50a	3113.6a	0.0	531.1a	3644.8a
Rice-Rice	0.68b	974.2b	702.4a	206.9b	1883.5b
Farm pond system	1.81c	608.2c	103.1b	97.3c	808.5c
Deep furrow & high ridge system	1.94c	783.7d	75.3c	117.2d	976.2d
Paddy cum fish system	1.78c	836.2d	63.3c	129.7d	1029.2d

Values with the same lowercase letters within land uses are not significantly different at $P < 0.05$.

Sundarbans region. In many cases crop failures primarily due to drought might be prevented through better water management at the farm-level. During periods when rainfall is insufficient, supplemental irrigation systems which are ex-situ water harvesting systems, ensure providing essential soil moisture to secure a good harvest. Supplemental irrigation a key strategy for unlocking rainfed yield potential and water productivity is however still underused (Rockstrom et al., 2010). Capturing runoff may also help prevent land degradation from water erosion, improve water quality, and allow use of harvested rainwater for supplemental irrigation as well as to control salt accumulation in the surface layer.

The land shaping models installed in the degraded areas not only favoured drainage but also lowered EC and improved soil quality while maintaining sufficient moisture in the surface soils. Therefore, the system is suitable for crop diversification in low lying areas of coastal degraded lands of the islands. About 279 ha of low productive salt affected land in Sundarbans has been converted from mono-cropped to multi-cropped with integrated crop and fish cultivation through implementation of different land shaping techniques (CSSRI, NAIP, 2014).

Most of the farmers in coastal region depend on their land for livelihood and thus in majority of the cases these farmers are hesitant to spare a portion of their land for the water harvesting structure considering it as uneconomical. Hence resource poor coastal farmers may not come forward to invest in land shaping techniques. In case of successful land shaping models, farmers must diversify their routine crops for maximizing profits. Periodic flooding and cyclonic storms in the region are anticipated to accelerate with climate change. As the region does not have any potential storage sites, the monsoon water would be a waste. Due to sea level rise and intrusion of saline water, coastal fresh and groundwater sources would likely become polluted. Salinity has become a problem over a large part of the coastal area mainly due to reduced surface water flow in the coastal rivers. Large scale adoption of land shaping may be solution to tackle the climate change impact in the region. Seasonal migration of labour to nearby cities is very common in the region and land shaping techniques check the migration of farm family by creating year round employment opportunities which have a great social impact.

A feasible strategy for realizing the potential of degraded coastal land in India (and elsewhere) appears to be intensification of integrated farming systems by harvesting a portion of the huge available surplus runoff through land shaping and using it for supplemental irrigation at the critical crop growth stages integrated with soil and water conservation practices and balanced plant nutrition.

4. Conclusion

Land shaping significantly reduced the salinity level and improved agronomic productivity of land. These technological interventions also enhanced farm income, increased cropping intensity and promoted crop diversification. Raised beds under vegetable cultivation ensured continuous supply of vegetables even during the peak monsoon period in islands and enabled quick return of the initial investment as well as providing nutritional security to the family. These technological interventions also generated higher employment opportunities in this impoverished region. Such interventions can be extended to similar coastal areas in other parts of the country and in similar tropical island systems elsewhere.

Accurate quantification of the impact of agricultural land use change on crop water footprint values still remains a challenging task, on account of important shortcomings in the availability of data and the complexity of agricultural activities and climate variability in the areas. Nonetheless, this study has quantified explicitly the impact of land shaping on water footprint and has uncovered a potential for alleviating water availability problems from the perspectives of agricultural land use optimization and integrated water management.

Acknowledgements

We thank the Director, ICAR-Central Soil Salinity Research Institute, Karnal for support. This research was supported by the ICAR-NICRA (National Innovations in Climate Resilient Agriculture). We are thankful to Apu Kumar Naiya, Apu Roy and Amit Kumar Jana for their help.

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